NeoBiota 63: 25–37 (2020)
doi: 10.3897/neobiota.63.55260
https://neobiota.pensoft.net

SHORT COMMUNICATION

A peer-reviewed open-access journal
NeoBiota
Advancing research on alien species and biological invasions

What are the economic costs of biological invasions? A complex topic requiring international and interdisciplinary expertise

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Academic editor: M. von der Lippe | Received 9 June 2020 | Accepted 23 September 2020 | Published 3 November 2020

Citation: Diagne C, Catford JA, Essl F, Nuñez MA, Courchamp F (2020) What are the economic costs of biological invasions? A complex topic requiring international and interdisciplinary expertise. NeoBiota 63: 25–37. https://doi.org/10.3897/neobiota.63.55260

Abstract

Biological invasions can cause substantial economic losses and expenses for management, as well as harm biodiversity, ecosystem services and human well-being. A comprehensive assessment of the economic costs of invasions is a challenging but essential prerequisite for efficient and sustainable management of invasive alien species. Indeed, these costs were shown to be inherently heterogeneous and complex to determine, and substantial knowledge gaps prevent a full understanding of their nature and distribution. Hence, the development of a still-missing global, standard framework for assessing and deciphering invasion costs is essential to identify effective management approaches and optimise legislation. The recent advent of the InvaCost database – the first comprehensive and harmonised compilation of the economic costs associated with biological invasions worldwide – offers unique opportunities to investigate these complex and diverse costs at different scales. Insights provided by such a dataset are likely to be greatest when a diverse range of experience and expertise are combined. For this purpose, an international and multidisciplinary workshop was held from 12th to 15th November 2019 near Paris (France) to launch several project papers based on the data available in InvaCost. Here, we highlight how the innovative research arising from this workshop offers a major step forward in invasion science. We collectively identified five core research opportunities that InvaCost can help to address: (i) decipher how existing costs of invasions are actually distributed in human

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society; (ii) bridge taxonomic and geographic gaps identified in the costs currently estimated; (iii) harmonise terminology and reporting of costs through a consensual and interdisciplinary framework; (iv) develop innovative methodological approaches to deal with cost estimations and assessments; and (v) provide cost-based information and tools for applied management of invasions. Moreover, we attribute part of the success of the workshop to its consideration of diversity, equity and societal engagement, which increased research efficiency, creativity and productivity. This workshop provides a strong foundation for substantially advancing our knowledge of invasion impacts, fosters the establishment of a dynamic collaborative network on the topic of invasion economics, and highlights new key features for future scientific meetings.

Keywords
Biological invasions, economic costs, innovative workshop, interdisciplinary skills

Context and rationale

Invasive alien species can negatively impact the environment, human health and socio-economy throughout the world (Bellard et al. 2016; Bradshaw et al. 2016; Bacher et al. 2018; Ogden et al. 2019). Worryingly, rates of introduction and establishment of alien species are rising and show no sign of abating (Seebens et al. 2017). Effective yet urgently needed mitigation of new invasions is still hindered by a lack of comprehensive information about their impacts (Latombe et al. 2017). Access to clear and usable information on worldwide invader impacts should help to improve public communication on invasion issues and coordinate trans-boundary efforts among policy makers and stakeholders (Courchamp et al. 2017). Describing the economic costs of invasions is a key way to effectively communicate the impact of invasion to a general audience (Caffrey et al. 2014; Diagne et al. 2020), and to help emphasise the importance of invasions in the global environmental agenda (Larson et al. 2011).

Biological invasions have diverse and complex economic costs to society (Bonn et al. 2005; Jackson 2015; Diagne et al. 2020). They include damage and losses (e.g., to infrastructure, human capital or crop production; Paini et al. 2016) – which can be direct (e.g., impacts on human health by disease transmission; Bradshaw et al. 2016) or indirect (e.g., damage repair following environmental degradation; Walsh et al. 2016) – and expenditures invested for avoiding or reducing the impacts of invasions through prevention, control or eradication (Hoffmann and Broadhurst 2016; Woodford et al. 2016; Alvarez and Solis 2019). This inherent heterogeneity, combined with a lack of clarity and consistency in invasion science terminology (Robertson et al. 2020), make the understanding and assessment of invasion costs challenging (Dana et al. 2013; Jackson 2015). The absence of a standard framework for assessing invasion costs means that many expenses linked to invasions may be overlooked. For instance, some indirect costs on human livelihoods (e.g., loss of income due to medical leave resulting from non-native pathogens; Selck et al. 2014) are often ignored. Moreover, an accurate valuation of invasion impacts is difficult, both methodologically (e.g., inadequate calculations, dubious mathematical assumptions; see Jackson et al. 2015 for an exhaustive overview) and ethically (e.g., valuation of living species, utilitarian view of

natural ecosystems) (Bradshaw et al. 2016; Hoffmann and Broadhurst 2016; Meinard et al. 2016). Addressing most of the challenges pointed out above requires a general view on the costs of invasions worldwide. Indeed, invasions represent a trans-boundary socio-ecological challenge; understanding – and then mitigating – their impacts relies on good global coverage as well as accurate and accessible data (Latombe et al. 2017; Pagad et al. 2018). This is particularly crucial given invasion costs may vary substantially over time, space, activity sectors or types of costs, even within a single taxonomic group (Bradshaw et al. 2016). Being aware of these variations is essential to identify effective management approaches and optimise legislation. In addition, actions and decisions should be taken at relevant scales by taking into account both inherent differences (e.g., invasion histories, financial capacity to invest in research and biosecurity) and connections (e.g., neighbouring countries, trade and transport networks) between areas (Chaffin et al. 2016; Faulkner et al. 2020). Consequently, a synthesis of the costs of invasions worldwide is topical and crucial for understanding the complex and context-specific nature of invasion costs. Unfortunately, studies that provided such a global-scale approach to the costs of invasions are so far either recognised as methodologically flawed, incomplete or outdated (e.g., Pimentel et al. 2005), or restricted to a single taxonomic group (e.g., insects; Bradshaw et al. 2016) or a particular economic sector (e.g., agriculture; Paini et al. 2016).

The new InvaCost database (Diagne et al. 2020) helps to meet this need by providing the first comprehensive compilation of the documented economic costs of invasive alien species globally. This updatable catalogue of 2419 cost estimates (extracted from 849 primary sources) and 46 variables, covering most taxa, geographical regions and activity sectors worldwide provides great opportunities to comprehensively assess and understand the economic impacts of invasions at different scales. The advent of the InvaCost database therefore provides unique opportunities to get a detailed picture of the economic impacts of invaders through integrative and novel approaches. Nonetheless, deciphering the complex nature of the economic costs of invasions through this unique dataset requires resources, skills and expertise from a range of disciplines (e.g., ecology, economics) and sectors (e.g., management, politics). To efficiently analyse these rich but complex data stored in the InvaCost database, an international and multidisciplinary workshop was held from 12th to 15th November 2019 near Paris, France.

The main objective of the workshop was to initiate studies from several research questions, share common approaches and tools for data investigation, and structure further work on each started project in a sustainable and high-quality science context. These scientific outputs are expected to bring novel evidence-based assessments that (1) could fully depict and predict the economic burden of invaders worldwide, (2) point out current biases and limitations for guiding further research, and (3) provide insights for efficient decision making by practitioners, and international and local authorities. Here, we provide a synthesis of this workshop and highlight the main features that seem relevant for other collaborative efforts in invasion science. Specifically, we (i) point out the key elements that contributed to the meeting's success, (ii) provide insights and outcomes from this workshop, and (iii) draw main conclusions and further perspectives from this event.

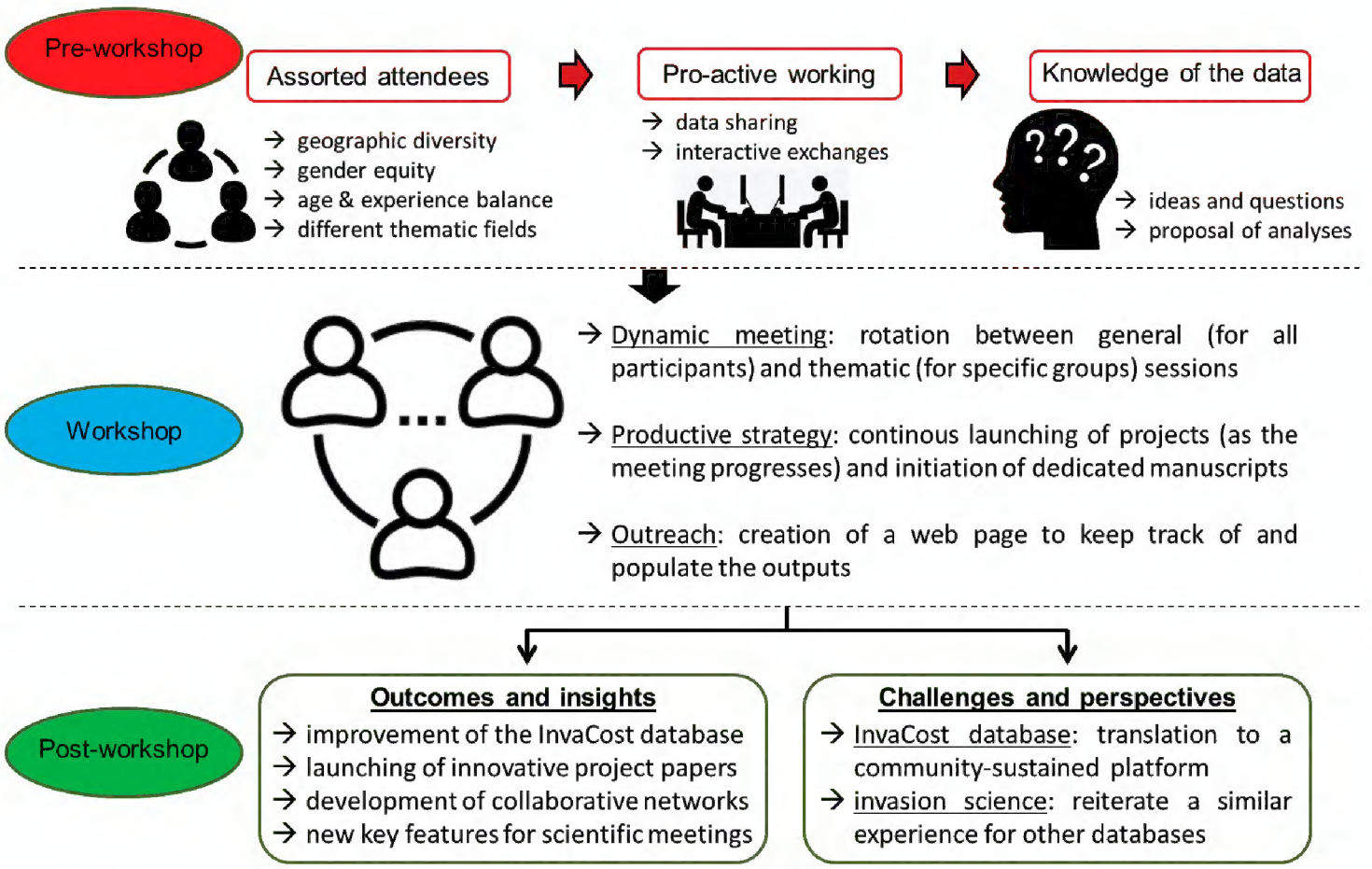

Figure 1. Chronological summary of the different steps and key features of the workshop.

Innovative elements for a fruitful workshop

The InvaCost workshop was designed to foster creativity and originality. This was achieved in six ways through the design of the workshop (Fig. 1).

Selecting assorted workshop participants

From over 130 applications, 36 attendees were selected based on their perceived motivation, skills, and interests. Six colleagues with complementary skills and expertise were also invited. Together with the members of the scientific organising committee, this resulted in 47 participants of whom about two thirds were early career researchers (PhD students, Post-doctoral fellows, early-stage researchers; Suppl. material 1).

Ensuring diversity and parity

The attendees represented 23 countries from all inhabited continents and about 45% of them were women, a proportion much higher than those classically observed in scholar publications (West et al. 2013) (Fig. 2). Equity and representation in working groups have been associated with higher quality science and positive societal outcomes (Campbell et al. 2013). This allowed to broaden the viewpoints and ideas, spark innovative and complementary ways of thinking, and boost the collective creativity.

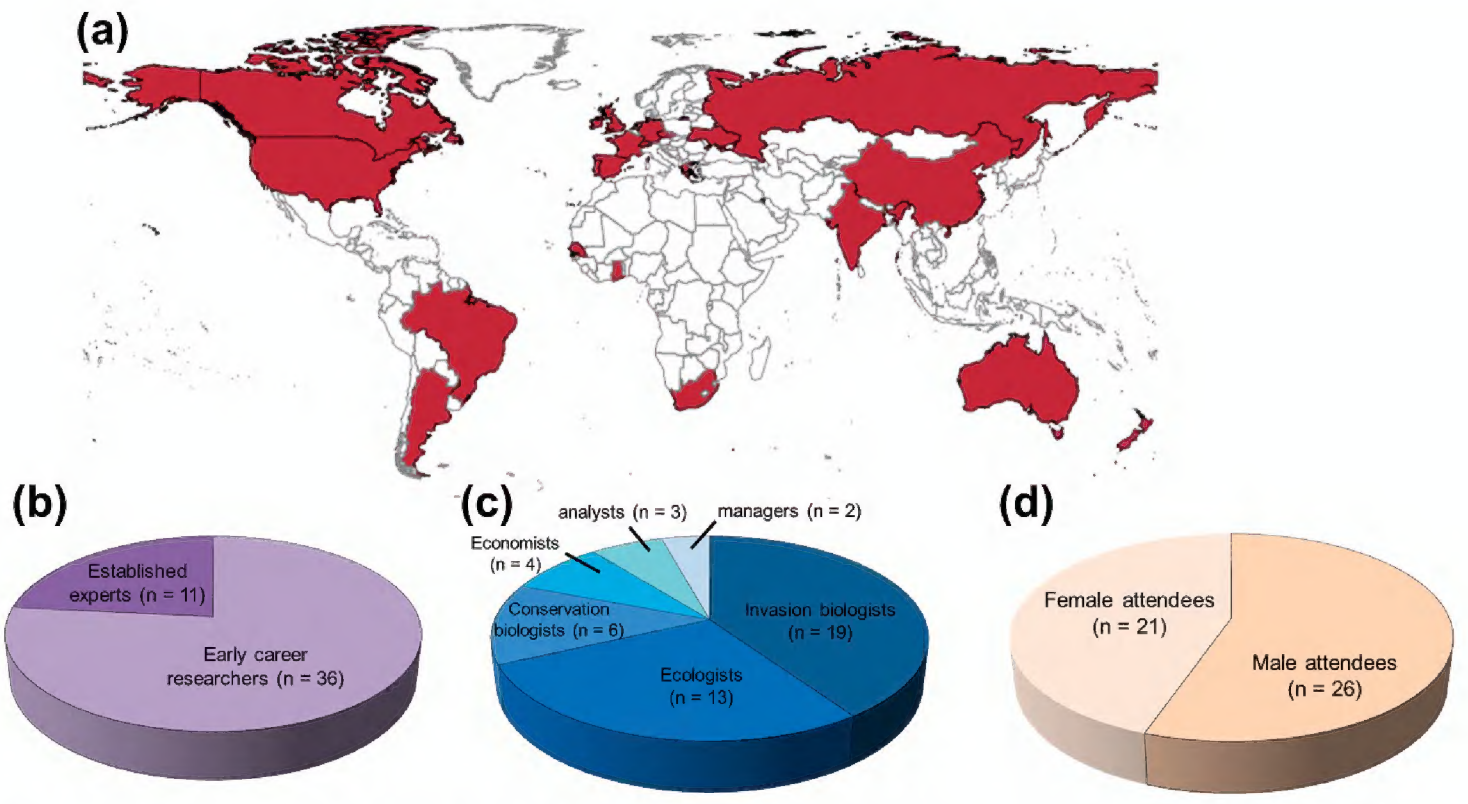

Figure 2. Graphical distribution of the attendees following their (**a**) nationality, (**b**) research experience, (**c**) working discipline and (**d**) gender. The different nationalities are represented by the countries highlighted in red (Argentina, Australia, Brazil, Canada, China, Czech Republic, France, Germany, Ghana, Greece, India, Ireland, Kuwait, Netherlands, New Zealand, Portugal, Russia, Senegal, South Africa, Spain, Switzerland, Ukraine, the United Kingdom and the United States). "n" represents the number of attendees.

Favouring a multidisciplinary and cross-sectoral approach

Fully understanding the heterogeneity of invasion costs requires expertise from various fields. The attendees were conservation biologists, environmental economists, invasion ecologists, biodiversity managers, modellers and data analysts (Fig. 2) who work on diverse taxonomic groups (animals, plants, microorganisms), realms (freshwater, marine, terrestrial) and activity sectors (e.g., agriculture, forestry, health, law and trade).

Organising an active pre-workshop phase

All participants were asked to familiarise themselves with the content of the database prior to the meeting. Concretely, participants were encouraged to collect and describe cost information in the dataset following the described methodology and procedures. This approach helped ensure that participants had an in-depth understanding of the database ahead of the workshop.

Creating a dynamic and inclusive work environment

The workshop alternated between general sessions for all participants in order to present talks and collectively discuss ideas, progress and perspectives; and thematic sessions for groups focusing on specific but rotating topics, with the aim of identifying analyses and thoughts for potential manuscripts.

Investing in outreach and engagement

A collective ResearchGate page (https://www.researchgate.net/project/InvaCost-assessing-the-economic-costs-of-biological-invasions) was created to keep track of and populate the overall output of the workshop with an updatable list of deliverables. In addition, communicating via social media was essential for promoting findings from this meeting in an accessible, interactive and understandable way to a variety of audiences. Furthermore, while the full long-term social costs of carbon emissions are likely not compensable (Essl et al. 2018), the organisers financially supported a project (https://kinome.fr/) to offset the total workshop's emissions' footprint associated with travels.

Outcomes and insights

During the workshop, we identified five core research opportunities that InvaCost can help to address (Table 1).

First, InvaCost offers unprecedented opportunities to provide the first global overview of the recorded economic costs. All attendees agree that a much-needed objective is to decipher how costs of invasions are actually distributed over space, taxa, society sectors and types of impacts. In that way, the global coverage (90 countries distributed across all continents) and the high taxonomic diversity (plants, vertebrates, invertebrates from both aquatic and terrestrial environments) of the database allowed us to initiate several draft manuscripts. Moreover, there was consensus among attendees that a crucial, yet unexplored topic is the identification of the ecological and socio-environmental drivers of invasion costs at different scales. Hence, specific projects were launched to analyse the relationships between invasion impacts and (*i*) management expenditure (e.g., investigating the damage costs of spreading aliens in relation with the spending on measures to prevent, control or eradicate them), (*ii*) activity sectors (e.g., describing how economic losses are distributed across the main production sectors such as fisheries, agriculture and forestry), and (*iii*) invader and recipient area traits (e.g., parameterising generalisable explanatory models that could be used to guide future management efforts).

Second, common gaps and biases in invasion research (Pyšek et al. 2008) were also detected in the cost data available, given they are spatially and taxonomically biased (Diagne et al. 2020). About two thirds of the cost entries belonged to North American and Oceanian regions, and 343 species were recorded while 869 species are actually registered in the Global Invasive Species Database (GISD, http://www.iucngisd.org/gisd/). To bridge these gaps, one-third of the attendees undertook extensive complementary data searches to expand the content of the database. The most illustrative example of this work package is the collection of cost information available in about 15 languages other than English. A preliminary data search has already suggested that the current number of cost entries in InvaCost could double. The diverse origin of the attendees represents a key asset to establish relevant local collaborations, and thus access to a large amount of information largely inaccessible to the international community as

Table 1. Examples of topics raised during the workshop, which are associated with research questions and ideas of project papers initiated during the workshop. GRIIS: Global Register of Introduced and Invasive Species (Pagad et al. 2018); SEICAT: Socio-Economic Impact Classification of Alien Species (Bacher et al. 2018)); GLMMs: generalised linear mixed models.

Issues raised from the database	Primary research questions	Examples of project papers
Cost estimates are multiple and depicted by numerous taxonomic, geographic, temporal, methodological, and habitat-related variables	What is the current distribution of the costs of invasions worldwide? Which ecological and societal variables are currently driving the distribution patterns of these costs?	Descriptive and inferential (e.g., meta-analysis, GLMMs) approach considering specific descriptors of the InvaCost database
Knowledge of cost information is fragmented as well as spatially and taxonomically biased	Which information and data are missing from the InvaCost database? What insights could they provide?	Synthesis of costs published in local, non-English reports globally; development of multidimensional extrapolation-based approaches
Relevant analysis of the cost data requires strong caution and several steps of data processing	How should the cost data be analysed to take into account the time lag between cost occurrences and cost reporting as well as the temporal dynamics of invasions?	Development of a R package that provides all basic functions and processing steps for fully analysing the costs of invasions
The economic costs of invasions are more complex and diverse than expected	How may invasion costs be harmonised to be unambiguously understood in the same way by different audiences?	A global conceptual, interdisciplinary framework for the economic costs of invasive alien species
Cost information is not stand-alone to assess the whole impact of invaders for prioritisation and management actions	How can cost data help to ensure a standardised assessment of alien species impacts across regions and to track potential changes over time?	Context-based insights for invader management from linking cost estimates to established indicators of alien impacts worldwide (e.g., GRIIS, SEICAT)

a whole. Further, we started to apply different methods to infer the fragmented cost information available at different scales (e.g., spatial, taxonomic, activity sector). The aim is to take into account societal and environmental features as well as research effort for accurately estimating the actual distribution and extent of costs. Novel statistical and mathematical methods (e.g., 'multidimensional extrapolation') – some based on existing approaches (e.g., Bayesian spatiotemporal risk models (Aukema et al. 2011)) – are therefore under development by the modelling specialists who attended the workshop.

Third, the content of InvaCost highlighted even more the complexity and heterogeneity of the economic costs of invasions. This situation is made worse by the lack of reporting consistency (Robertson et al. 2020) that may hamper consistent data categorisation. For instance, the database evidenced that the term 'control' is often dubiously used in reports and articles to represent different types of management actions. Ultimately, this lack of framework could lead to misconceptions and limited understanding in scientific and non-scientific communities. Hence, the group attendees recognised the strong need to harmonise terminology and concepts for both research and management purposes. A study was therefore initiated to build a robust and consensual framework at the interface of the different disciplines devoted to study these economic costs of invasions. The objective is not to create an unrealistic, universal framework that should apply to all approaches and thoughts. Our ambition is rather to develop a dynamic framework integrating a holistic, but standardised set of definitions underlying the 'economic costs of invasions'.

Fourth, analysing the content of the database in the most relevant way requires a cautious approach (Diagne et al. 2020). Indeed, cost information were not categorised

in InvaCost within a working framework directly implementable for all types of studies. For instance, while obvious duplicate cost estimates (i.e., same cost figures from different sources) were removed when building the database, some overlaps may still occur in the dataset. This could be the case for some taxa when recent cost entries incorporate older ones, or when cost entries cover a large spatial scale that could include some costs provided at smaller scales. To help future users in appropriately investigating the data available, we started to create a dedicated R package (called 'invacost'; Leroy et al. in prep). This package aimed to implement (i) all basic instructions to fully understand the global database and its statistic requirements, (ii) necessary processing steps for getting the most relevant subsets, and (iii) a range of diverse approaches and methods (e.g., ensemble modelling) to derive the cumulated, average and expected cost values over time for each category of the descriptive variables.

Fifth, one of the ultimate goals in invasion research is to provide information and tools that will be useful for mitigating the impacts of invasions. This requires standardised assessments of invader impacts across regions and over time, while considering the societal and policy components of invasions (e.g., Kapitza et al. 2019). In that sense, studies were launched to (i) link cost information to established indicators of alien impacts worldwide (i.e., Global Register of Introduced and Invasive Species, GRIIS; Pagad et al. 2018); Socio-Economic Impact Classification of Alien Species, SEICAT; Bacher et al. 2018), (ii) assess the ambivalence of some invasive alien species (e.g., comparing costs and benefits in specific areas or for specific sectors), and (iii) investigate the relationships between invasion costs and diverse societal components (e.g., human attitudes and perception via an invasion culturomics approach; Jarić et al. in press). The other – complementary – way to reach this objective is to estimate how financial tolls of invasions may vary in relation to a changing global environment. Indeed, predictive approaches have been increasingly recognised as of prime relevance to alert societies to potential future risks and support cost-effective management strategies (Essl et al. 2019). Cost information will be used to strengthen quantitative models of future trajectories and outcomes of invasions (Lenzner et al. 2019). Typically, such an approach would allow evaluation and prioritisation of political and management options according to several scenarios of invasions (Essl et al. 2019). This perspective puts even more emphasis on the need for transdisciplinary collaborations among scientists, practitioners and decision makers.

Conclusions and perspectives

There is a strong need to involve an international and multidisciplinary group of scholars when dealing with the economic costs of invasions. Our workshop generated a substantial number of descriptive, methodological and conceptual projects that will substantially advance knowledge of invasion economics. The workshop also fostered the establishment of a dynamic collaborative network that is extended beyond the attendees

to this workshop, thanks to the multiple origins and diverse disciplines of the attendees. Any new researcher or stakeholder interested in contributing to, or extending, the topics presented here may join this open network by contacting any of the attendees of our workshop (Suppl. material 1). Hence, our network on this project has already been extended to 83 members from 32 countries following this workshop – at the time of writing this paper. The original database is intended to be regularly updated with new cost information (Diagne et al. 2020). Having an international community around InvaCost would thus be highly beneficial for both the scientific community and stakeholders. Therefore, further translating InvaCost to an official cost register for information delivery to decision makers would allow the sustainability of the global project (see Pagad et al. 2018 for a similar initiative) while ensuring information relevance and transparency as the database is expanded and used. Indeed, we envision that this database will be ultimately hosted on a stable personal website, which would allow crossing information with other relevant information sources on invasive species (e.g. GISD, http://www.iucngisd.org/gisd/). This website could rely on existing well-recognised international systems (e.g. Global Biodiversity Information Facility; GBIF.org) for ensuring sustainability and information flow towards a broad and varied community.

Moreover, our work provides a springboard for further research in invasion science, beyond the scope of the economic costs. Indeed, it creates major opportunities for catalysing concerted research on broader invasion impacts. Especially, an appealing research avenue should be to link economic costs and ecological impacts of invasions, with the aim to provide semi-quantitative metrics for both aspects of the effects of invaders. Furthermore, we also encourage future committees to routinely consider the key features highlighted here (assorted, fair and balanced working group, active pre-workshop phase, transparent communication and environmental compensation) when organising scientific workshops. Interestingly, most of these features can be applied even for remote events, which are increasingly considered as a sustainable alternative to conventional meetings (Porpiglia et al. 2020). Typically, it should be exciting to recreate a similar experience for other existing or developing databases (e.g. Dyer et al. 2017; Pagad et al. 2018; van Kleunen et al. 2019) investigating different facets of invasions.

Funding

This workshop was funded through generous support by the ECOMOB programme (funded by the French Centre National de la Recherche Scientifique), the Université Paris Saclay (Department of Biology) and the AXA Research Fund through the Invasion Biology Chair. We acknowledge the French National Research Agency (ANR-14-CE02-0021) and the BNP-Paribas Foundation for providing funds to the InvaCost project that led to the construction of the database. The organisers and FE appreciate funding by the AlienScenarios project (FWF project no I 4011-B32).

Acknowledgements

We are extremely grateful to Marion Cordonnier for her active involvement in organising this event. We also thank Elsa Bonnaud, Céline Bellard and Camille Bernery for their valuable contributions during the workshop. We express our gratitude to Liliana Ballesteros-Mejia for her help with a graphical item. We appreciate the helpful comments and feedback from Moritz von der Lippe, Benjamin Hoffmann and an anonymous reviewer.

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Supplementary material 1

List of participants and associated information

Authors: Christophe Diagne, Jane A. Catford, Franz Essl, Martin A. Nuñez, Franck Courchamp

Data type: table

Explanation note: Names and affiliations of participants attending to the workshop.

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Link: https://doi.org/10.3897/neobiota.63.55260.suppl1